Comparative analysis of stress distributions and displacements in rigid and flexible pavements via finite element method

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Abstract
In many countries of the world, rigid and flexible pavements are widely used. Some of the external factors such as stresses and displacements play major role in the design of pavement layers such as coating, base and sub-base. Although empirical formulas and methods were used in the calculation and design of the pavement layers, complexity of today's transportation engineering demands effectiveness of the empirical formulas were diminished. Nowadays complex problems can be easily simulated and solved thanks to the higher analysis capabilities of the computer-aided softwares. In this study, the stress distributions and displacements were examined under traffic loads in rigid and flexible pavements with different coating layer thicknesses (30 mm, 50mm, 70mm, 100 mm, and 150 mm) by using finite element method. As a result, the vertical displacement in the flexible pavements were obtained as 5% higher than the vertical displacement in the rigid pavements. Based on the stress distribution results, the stress values of flexible pavements were 60% lower than the stress values of the rigid pavements. Moreover, It was determined that the stresses in the rigid pavements remain in the coating layer, while the stresses in the flexible pavements reach the base and sub-base. In addition, regression models have been developed to predict stress and displacements by using layer thicknesses. High correlation and determination coefficient values (> 0.90) were achieved based on the regression analysis both in flexible and rigid pavements.

Keywords: rigid and flexible pavements, ANSYS, stress, displacement, layer thickness.

Introduction

Flexible and rigid pavements are the most commonly used pavement types on roads today. Flexible pavements are designed for a service life of 20 years and construction, maintenance and repair costs of flexible pavements are higher than rigid pavements. Rutting problems are disadvantageous in terms of safety and comfort in the flexible pavements (Tinni & Consulting, 2013). As the wheel load will be distributed over a wider area on flexible pavements, the stresses will decrease with the depth of pavement. Due to this behaviour of flexible pavements, they have to build in a layered structure in order to reduce the cost of road construction (Mathew & Rao, 2006). On the other hand, rigid pavements can be more economic in terms of construction and maintenance costs than flexible pavements. Besides, the most important advantage of rigid pavement is that they are resistant to heavy traffic loads and severe environmental conditions (Mohod & Kadam, 2016). Although these two pavements types have advantages and disadvantages compared to each other, conditions such as traffic density, environmental conditions, economy and service life should be taken into consideration while designing the pavement. In the road design, different layers are established in the rigid and flexible pavements construction. Compressive and tensile stresses occurring in the coating layer may cause rutting and fatigue cracks on the road. Maximum stresses under the wheels varies depending on the depth and the horizontal distance between axles (Walubita & Van de Ven, 2000). Determination of stresses and displacement have an important role for the selection and design of the pavement type. The main purpose of pavement design is to determine the layer thicknesses that can safely carry the traffic loads, without major deformations and cracks in the pavement (Ağar, Öztaş & Sütaş, 1998).

Empirical methods were evaluated in AASHTO (American Association of State Highway and Transportation Officials) regulations in pavement designs until 1993 (Özcanan & Akpınar, 2014). Recently, in most of the cases designing a road pavement via empirical methods is insufficient since many factors that affect the performance of the pavement. For these reasons, the pavement design becomes complex. With the help of computer-based calculations, after 1993, AASHTO has made improvements on mechanistic design methods as well as empirical studies. In the literature, the finite element method is used in the mechanistic design. Many comprehensive and time consuming calculations can be easily analyzed in a very short time with the finite element method. Using the finite element method in pavement design provides a great opportunity in determining the bearing capacity as well as the stresses and deformations in the pavement and sub-layers (Calvarano, Palamara, Leonardi & Moraci, 2017; Li, & Hu, 2018; Leonardi, 2015).

The finite element method, which was used in aircraft engineering applications in the 1950s (Jin, 2015), the first pavement analysis based on finite element method was established by Duncan et.al (1968). In general, finite element analysis takes into account the theory of multilayered road systems developed by Burmister (1945) (Ağar, Öztaş & Sütaş, 1998). Although, linear elastic materials were used with the finite element method at first, today it is possible to make linear and nonlinear two-dimensional (2D) and three-dimensional (3D) dynamic and static analyzes, thanks to computer technology. Moreover, there is no limit to the number of layers and material in the finite element analysis recently (Yanov & Zelepugin, 2019).

Although there are plenty of the studies has been performed on flexible and rigid pavements, most of these studies are based on empirical methods (Wang, Li, Wen & Muhunthan, 2020; Sun, Han, Fei, Guo & Zhang, 2020; Wood & Donnell, 2020; Shirzad, Aguirre, Bonilla, Elseifi, Cooper & Mohammad, 2018). In the study held by Çelik (2014), samples taken from flexible and rigid pavements were tested in the laboratory and the flexible pavement material model was conducted via finite element model with the elastic assumption. Gevrek (2008) have analysed the stress distributions by 2D finite element analysis on flexible pavements (Leonardi, 2015). Shoukry et al (20011), investigated the effects of traffic load and temperature factors on the triaxial stresses around the reinforcement with the Ls-Dyna finite element program in reinforced rigid pavement (Shoukry, William & Riad, 2011). In the study conducted by Shoukry et al (2008) on the solution of thermo-elastic asphalt and road material problems exhibiting nonlinear behavior, the deformations in the horizontal direction were investigated by comparing the finite element model with the data taken from the field (Shoukry, William & Riad, 2008). Taghipoor et al (2020) used finite element method to model the fatigue behavior of glassphalt and conventional mixtures.

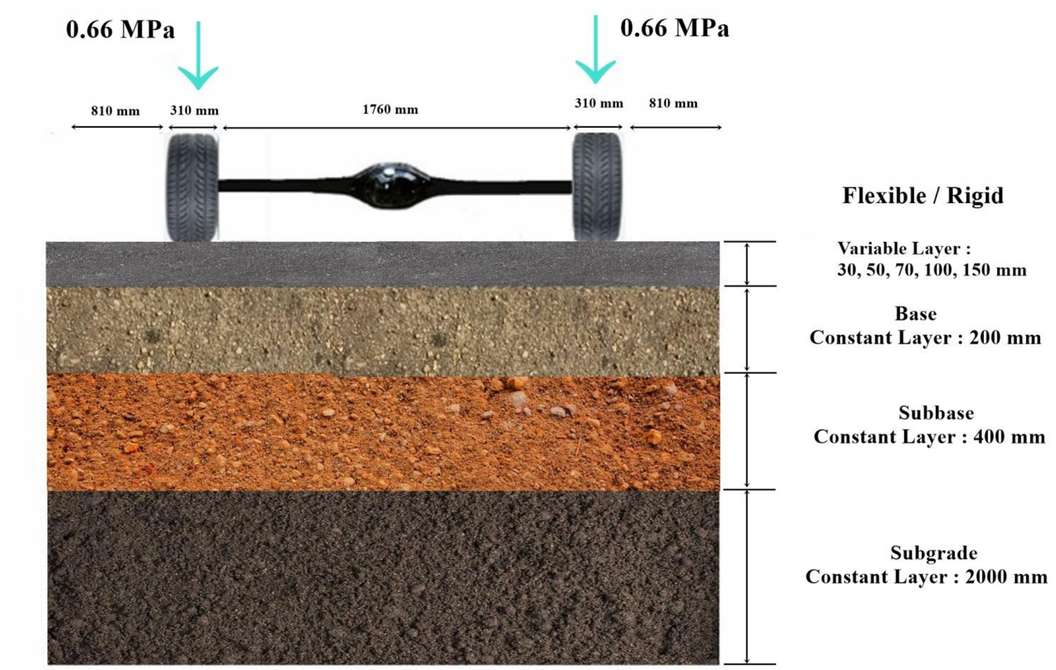
As understood from literature, either flexible or rigid pavements were analysed individually in studies conducted up to now. On the other hand, there are few studies were investigated both rigid and flexible pavement all together and most of them were theoretical and review studies. For that reason, in this study, the effect of different layer thicknesses on stress and displacement behaviour of flexible and rigid pavements were investigated and compared using finite element analysis by the help of ANSYS.

Thus, in the study, stress distributions and displacement values due to traffic loads in flexible and rigid pavements with different thicknesses (30 mm, 50 mm, 70 mm, 100 mm, 150 mm) were comparatively investigated. Using the ANSYS V.19 (ANSYS, 2019) finite element software, three-dimensional (3D) nonlinear analyzes of the pavement models were examined. In addition, based on the results by using ANSYS model, regression estimations were developed for both stress and displacements.

Materials and method

In this study, stress distributions in flexible and rigid pavements are investigated. In order to compare the effect of the thickness change in the coating layer on the stress, the thicknesses of the base, subbase and subgrade layers were kept constant. A total of 10 different pavement models, with coating layer thickness of 30 mm, 50 mm, 70 mm, 100 mm and 150 mm, were established on the ANSYS program. After that, these models are divided into two groups and 5 of them are designed as rigid pavements, while 5 are designed as flexible pavements. Figure 1 shows the pavement cross-section and loading condition. The loads from the wheels were applied as the standard equivalent single axle load of 80442 N (8.2 tons). Since the definition of stress instead of single loads in the finite element method gives more accurate results, the calculated axle loads were applied as 0.66 MPa stress in the analysis.

Figure 1. Flexible and Rigid Pavement Cross Section. (Self-Elaboration).



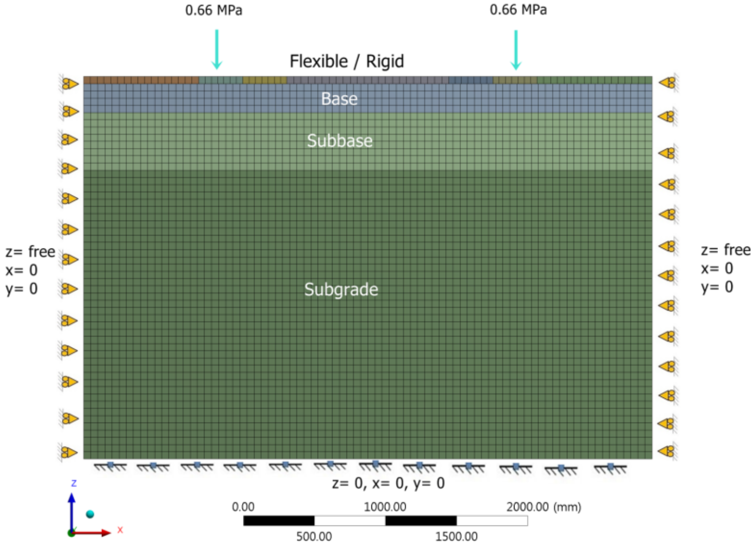
In this study, a visco-elastic material whose strength varies depending on the loading and temperature is used for the analysis of flexible pavement. The shear and bulk modulus values of viscoelastic material with respect to time were supplied from the study of Mulungye et al. (2007) (Mulungye, Owende & Mellon, 2007). On the other hand, elastic material model, can be used for concrete material in engineering designs, were used for base, subbase and subgrade layers (Erdogan, 2003; Mindess, Young & Darwin, 1981). C25 grade concrete material were selected for the RP layer. Properties of the material used in this study are shown in Table 1.

Table 1. Material Properties. (Self-Elaboration).

Layers	Modulus of Elasticity (MPa)	Poisson Ratio	Density (kg/m^3)
Flexible Pavement	3500	0.40	2400
Rigid Pavement	30000	0.18	2450
Base	600	0.40	2200
Subbase	100	0.30	2200
Subgrade	30	0.40	2200

Cubic mesh elements of 50x50x50mm were selected in finite elements as shown in Figure 2. As the boundary conditions, both lateral and vertical movements were not allowed under the subgrade layer. In the lateral borders of the model, only vertical movements are allowed in the model. Briefly, the base of the model was defined as a fixed support and a roller support was used on the lateral surfaces as seen in Figure 2.

Figure 2. ANSYS finite element model, boundary conditions and load case. (Self-Elaboration).



After analysis of finite element model equivalent stress and total deformations were obtained to evaluate the effects of layer thickness on flexible and rigid pavements. Equivalent stresses and total deformations in the analysis are based on 3D analysis. More specifically, graphs were created by gathering the data on a line (2D) on the contact surface between the wheel and the coting layer. Finally, regression models were conducted based on these data.

Results and discussion

In this study, the deflections and stress distributions of flexible and rigid pavements according to different layer thicknesses are comparatively investigated. Figure 3 demonstrates equivalent stress (von-mises) distribution in flexible pavements. In Figure 3, it is observed that the equivalent stresses calculated for flexible pavements increase with the decrease in layer thickness. In the analyses of different layer thicknesses in flexible pavements, the highest equivalent stress value was obtained with 2.81 MPa at the 30mm layer thickness. In addition, the lowest equivalent stress value in the models of flexible pavements was obtained as 1.95 MPa at the 150mm layer thickness.

Figure 3. Equivalent stress (von-mises) distribution in all flexible pavement models. (Self-Elaboration).

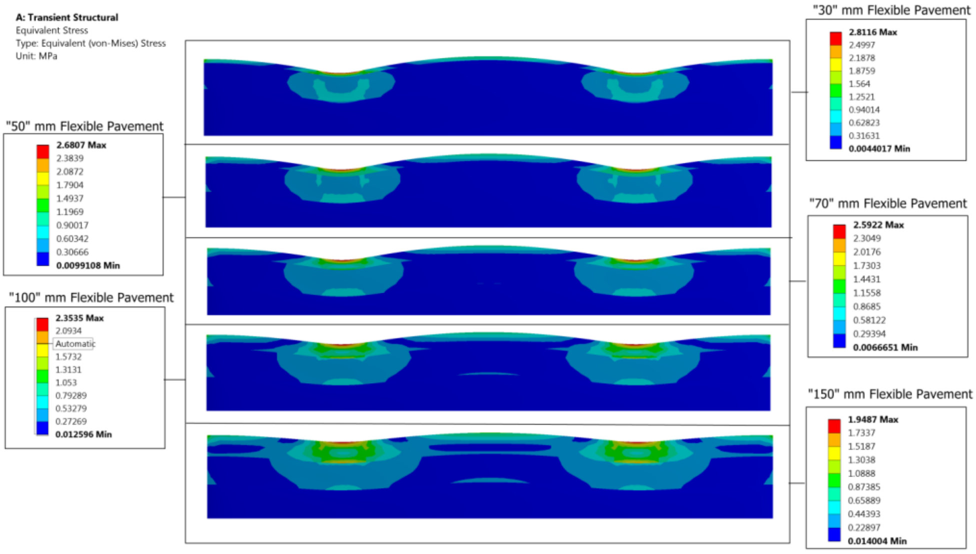
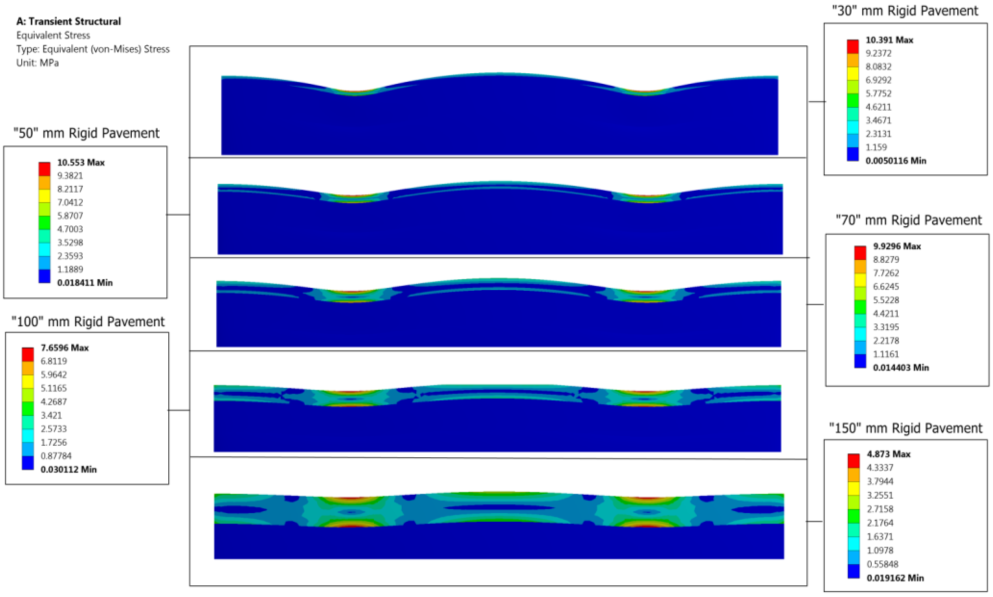


Figure 4 shows the variation of the equivalent stress (von-mises) values calculated for rigid pavements with different layer thicknesses. The lowest equivalent stress value was observed at the 150 mm layer thickness while the highest equivalent stress value was observed at the 50 mm layer thickness. The highest equivalent stress values were obtained as 10.55 MPa, and the lowest equivalent stress values were obtained as 4.87 MPa.

Figure 4. Equivalent stress (von-mises) distribution in rigid pavement models. (Self-Elaboration).



After the 3D analyzes, the graphs created by using the 2D stress values taken from the surface between the wheel and the coating layer in the x direction are presented in Figure 5. In this way, it was aimed to examine the effects of different layer thicknesses on stress distribution in the cross section of flexible and rigid pavements. 2D stresses in flexible pavements were between 2.37 MPa and 3.25 MPa based on Figure 5. On the other hand, it is seen that stresses in rigid pavements were between 5.12 MPa and 10.83 MPa. When the stress analysis, under the contact area between wheel and coating layer, for each coating thickness are examined, it is understood that the stresses in flexible pavements are lower than rigid pavements.

Figure 5. Equivalent stress (von-mises) distribution in rigid pavement models. (Self-Elaboration).

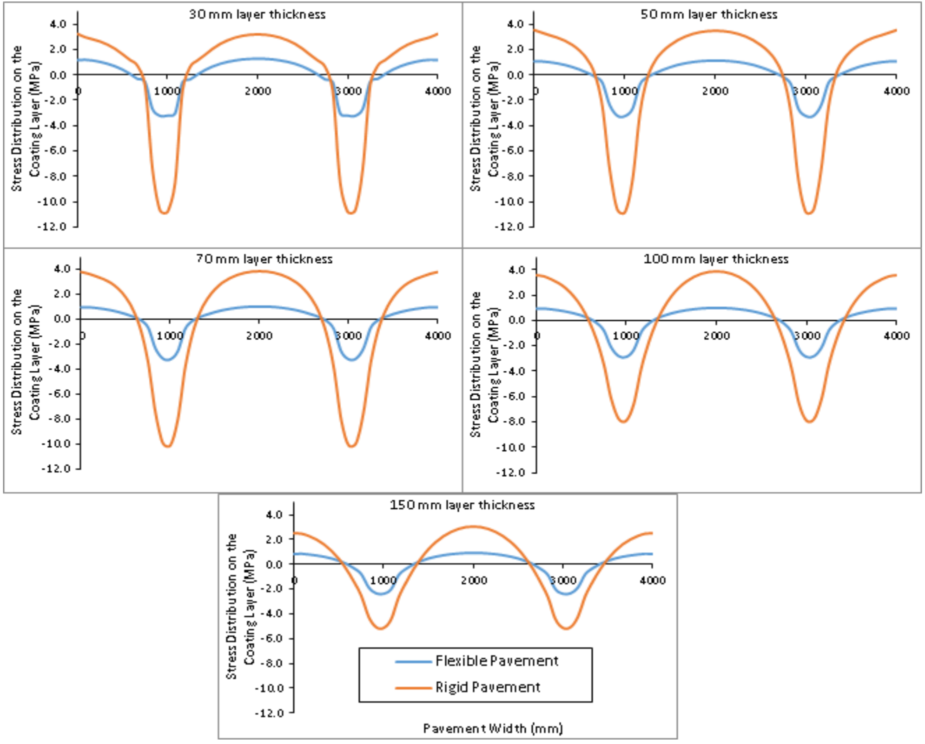


Figure 6 was demonstrated to compare the maximum stresses occurred for each layer in the z direction. Thus, stress variations in different layers for rigid and flexible pavements could be studied. It is understood that the stress value (z direction) occured under the wheel in flexible pavements was reduced by 5.48% in the base layer, while this decrease were achieved by 26.69% in rigid pavement.

Figure 6. 2D Stresses in z-direction. (Self-Elaboration).

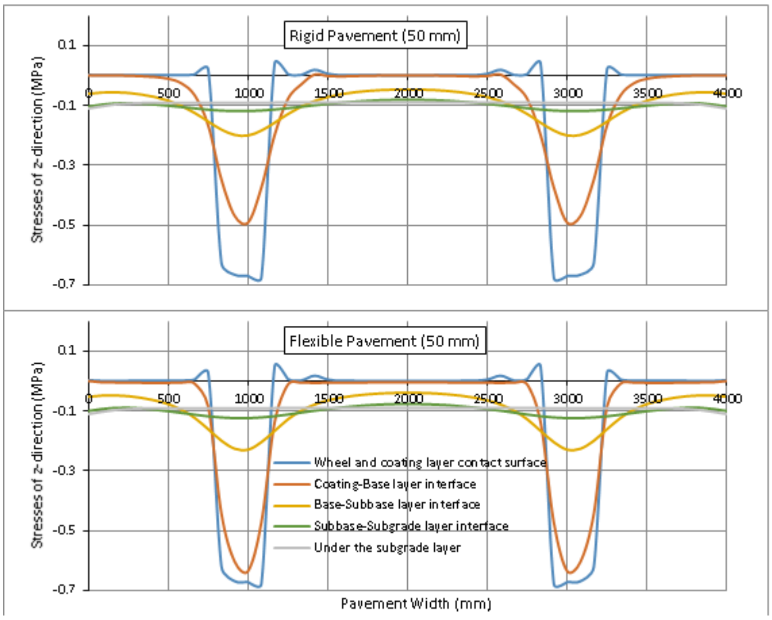
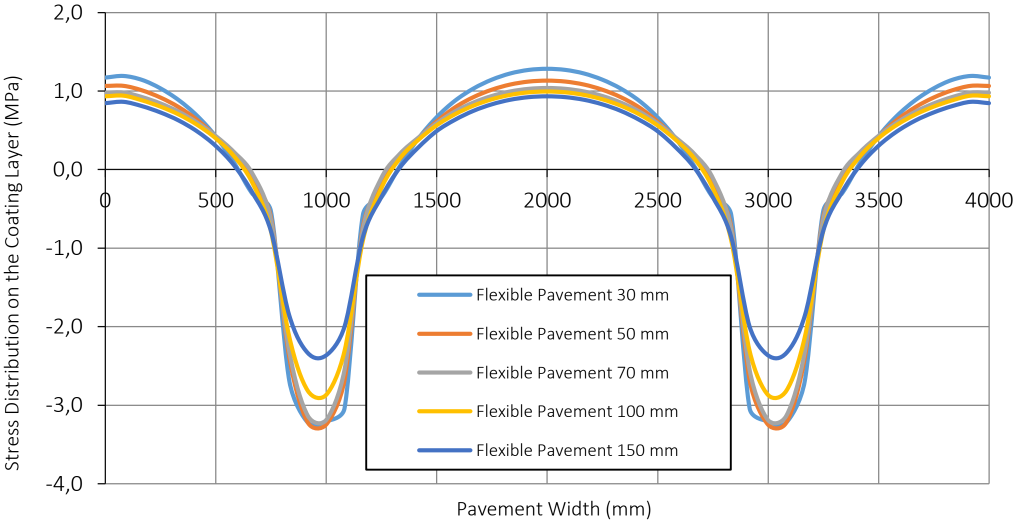


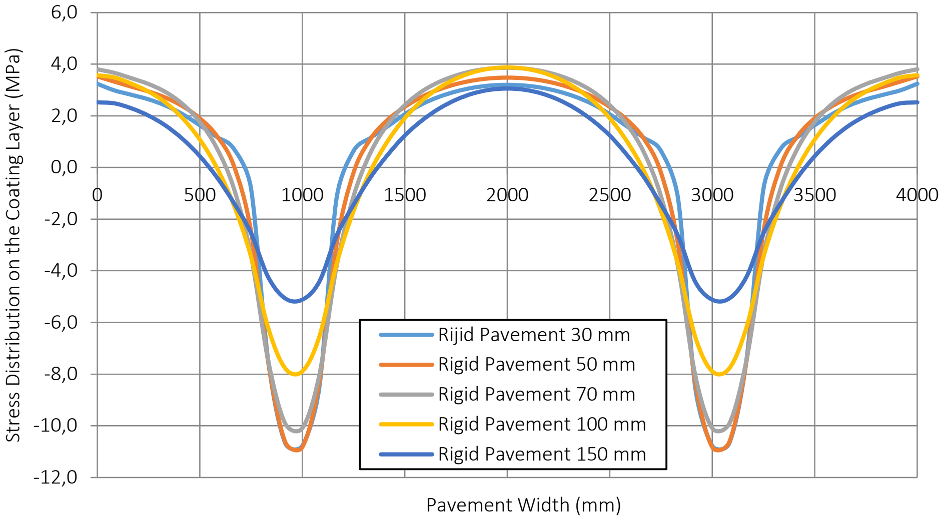
Figure 6 indicates that the stresses on the z-direction in rigid pavements for the same layer thickness (50 mm) show a drastic decrease compared to the flexible pavement throughout lower layers. These values obtained in terms of comparison of the maximum stresses in different layers are in agreement with the literature information given for flexible and rigid pavements. Figure 7 shows variations of the stress distribute on for flexible pavement with different layer thicknesses. It was seen that as the coating thickness increases, the stress values decrease. The maximum stress occurred in the model with 50 mm coating thickness and the tensile value was 3.25 MPa. The minimum stress occurred in the model with a 150 mm coating thickness with a tensile value of 2.37 MPa.

Figure 7. Comparison of 2D stress distributions in x-direction of all flexible pavements. (Self-Elaboration).



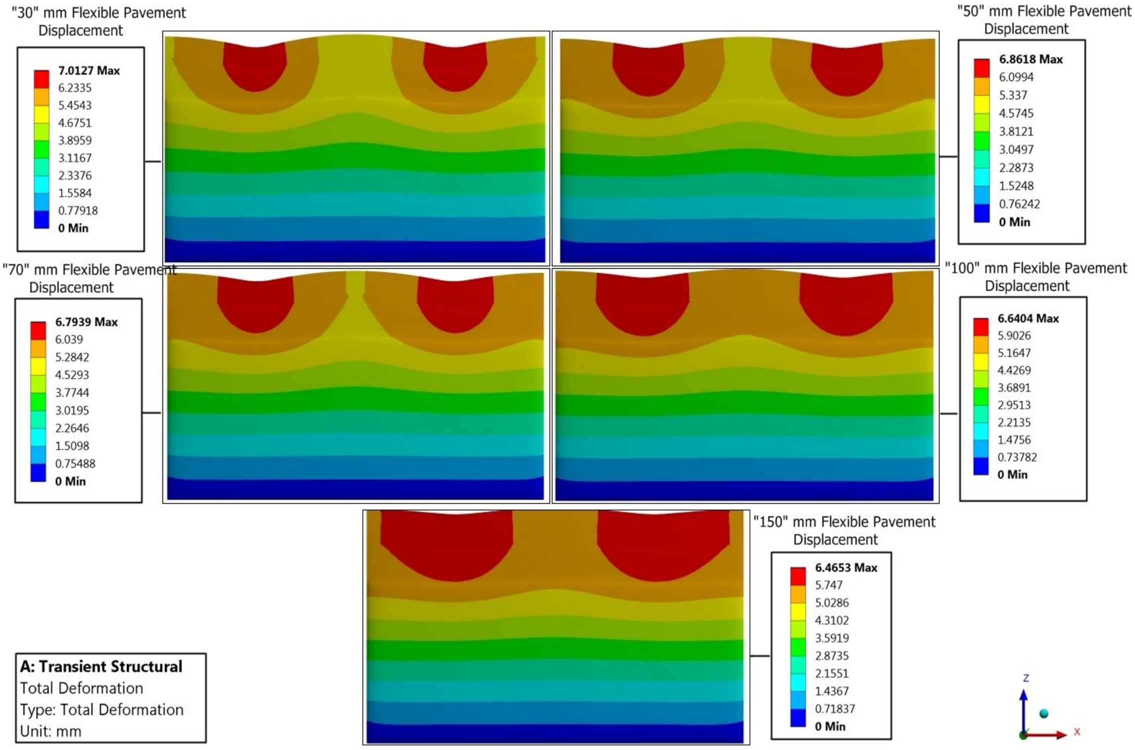
It can be seen in Figure 8 that the stress distribution tends to decrease as the thickness of the coating layer increases in rigid pavements. Moreover, the lowest stress value was 5.12 MPa in the coating layer of 150 mm, and the highest stress value was 10.83 MPa in the coating layer of 50 mm.

Figure 8. Comparison of 2D stress distributions in x-direction of all rigid pavements. (Self-Elaboration).



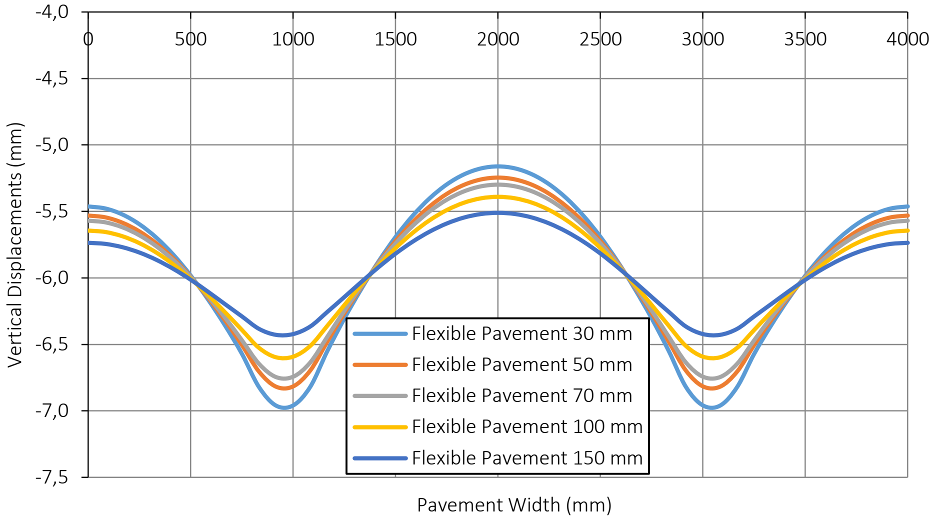
When the deflections as a result of the analysis were examined, the displacement of both flexible and rigid pavements decreased as the thickness of the pavement layer increased. In both pavement models, the maximum displacement occurs just below the point where the wheel load affects. Considering the same load and layer thickness, in flexible pavements the displacements are 5% higher than the rigid pavements. Displacement values of flexible pavement were shown in Figure 9.

Figure 9. Displacements for flexible pavement models. (Self-Elaboration).



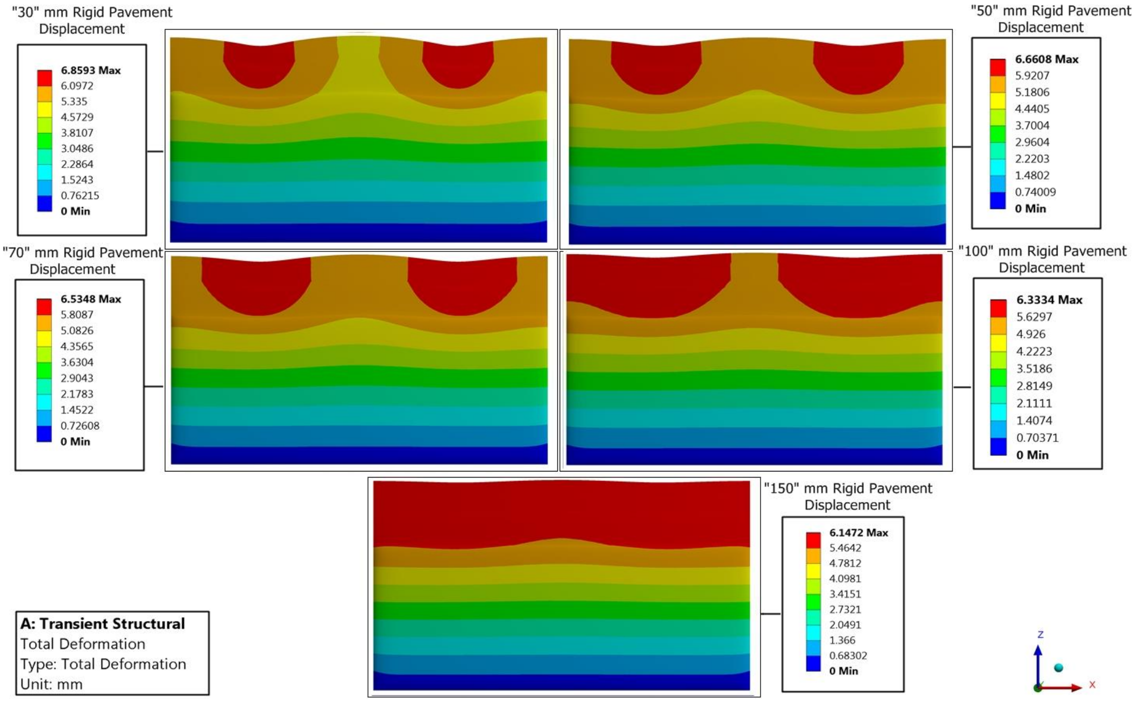
The displacement values in flexible pavement models with 30 mm, 50 mm, 70 mm, 100 mm and 150 mm coating thickness were shown in Figure 10. The minimum displacement was 6.46 mm in the model with 150 mm coating thickness, while the maximum displacement was 7.01 mm in the model with 30 mm coating thickness.

Figure 10. Displacements in flexible pavements. (Self-Elaboration).



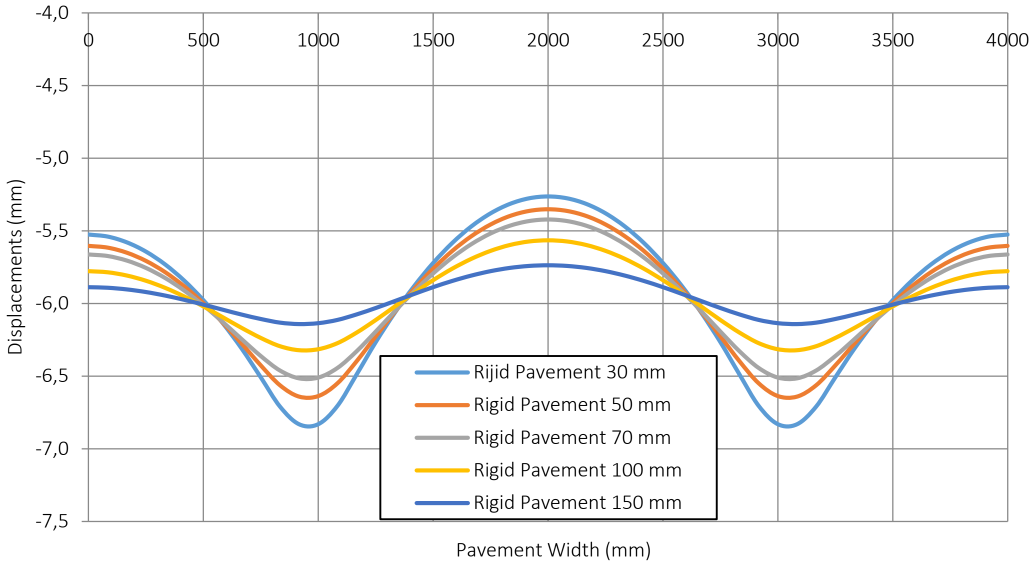
Changes in displacement values in rigid pavement models were shown in Figure 11.

Figure 11. Displacements in rigid pavements. (Self-Elaboration).



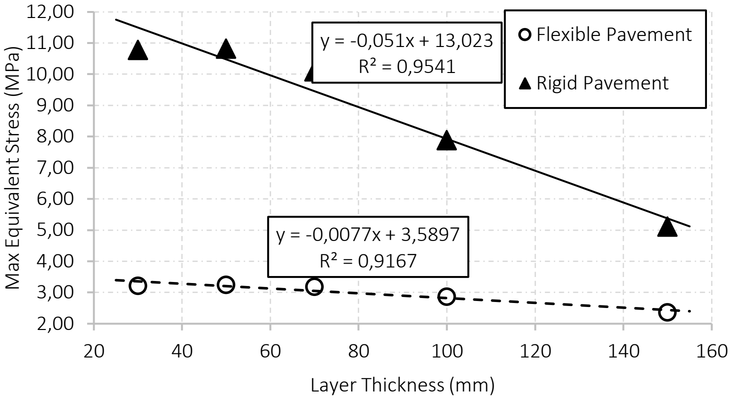
The displacement values in rigid pavement models with different thicknesses between 30 mm and 150 mm were shown in Figure 12. The minimum displacement was 6.14 mm in the model with 150 mm coating thickness, while the maximum displacement was 6.85 mm in the model with 30 mm coating thickness.

Figure 12. Displacements in rigid pavements. (Self-Elaboration).



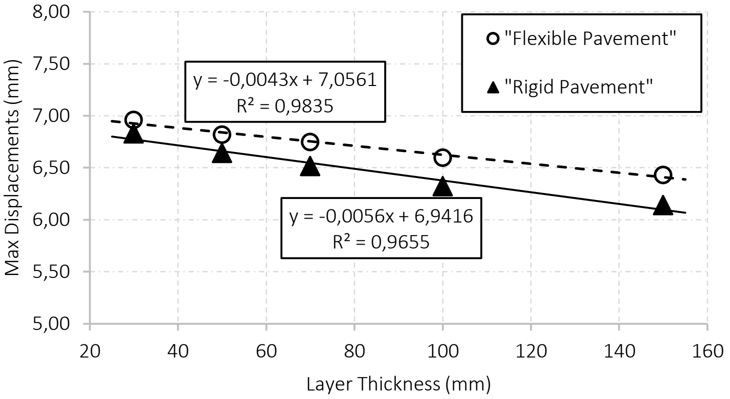
By using the results of finite element analysis a linear regression model were established between the stresses and layer thicknesses for both flexible and rigid pavements (Figure 13). The determination coefficient (R^2) of the model established for flexible pavements was obtained as 0.917. The R^2 value was 0.954 in the regression model established for rigid pavements. It that way to predict stresses values based on layer thicknesses with high reliability, and it is possible to calculate the maximum stress value with the help of the model for any layer thicknesses.

Figure 13. Relationship between layer thicknesses and stresses based on regression model. (Self-Elaboration).



The estimation model showing the relationship between layer thickness and displacement for both pavement types were presented in Figure 14. In the model for flexible pavements, displacement values corresponding to layer thicknesses were estimated with 0.984 (R^2). Besides, in the rigid pavement model R^2 value was obtained 0.966. Also, it is possible to predict displacement values based on layer thicknesses with high correlation in this regression model.

Figure 14. Relationship between layer thicknesses and displacement based on regression model. (Self-Elaboration).



It is seen that the estimation models established for both flexible and rigid pavements have high estimation capability. Moreover, it is also remarkable that the displacement estimations give better results than stress estimations.

Conclusion

Comparative analysis of flexible and rigid pavement models with different coating layers under the same axle load was performed using the finite element method. It was determined that the maximum equivalent stresses and total displacements in both pavements were obtained in contact area of wheel and coating layer. The variation between maximum and minimum displacement in flexible pavements was found to be 8.5%. On the other hand, the minimum displacement in the rigid pavement obtained as 6.14 mm in the model with 150 mm coating thickness, while the maximum displacement obtained as 6.85 mm in the model with 30 mm coating thickness. In rigid pavements, the variation between maximum and minimum displacement was 11.5%. As a result of the analysis, it was seen that the displacement in the flexible pavement was 5% higher than the displacement in the rigid pavement. In both flexible and rigid pavements, it was observed that as the layer thickness increased, the amount of displacement decreased.

When the finite element models were examined, the stresses formed decreased as the thickness of the coating layer increased in both flexible and rigid pavements. It was determined that the stresses in the flexible pavement models vary between 2.10 MPa and 3.20 MPa. There was a 52.30% variation between maximum and minimum stresses. The stress values was between 5.20 MPa and 10.80 MPa, when the stress distributions in rigid pavement models are examined. There was a 108% variation between maximum and minimum stress. The results showed that the maximum equivalent stress values in the flexible pavement were lower than the maximum equivalent stress values in the rigid pavement between coating layer and base layer. On the regression estimation models established for both flexible and rigid pavements showed very high (>0.90) determination coefficient (R^2). Based on the test result it is concluded that the established regression model could be predict efficient layer thicknesses in both rigid and flexible pavement designs.

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